

# Grain Alignment, Polarization and Magnetic Fields

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## Abstract

Aligned non-spherical dust particles polarize starlight passing through the dust cloud. They also emit polarized far infrared and sub-mm radiation. Substantial progress in understanding of grain alignment theory makes the interpretation of the polarized radiation in terms of underlying magnetic fields much more reliable. I discuss a number of fundamental processes that affect grain alignment. In particular, I shall discuss how subtle effects related to nuclear spins of the atoms alter the dynamics of dust grains. I shall discuss how the theory explains the existing observational data and demonstrate when the polarization can and cannot be interpreted in terms of the underlying magnetic fields.

## 1 History of ideas

Observations by [9, 10] revealed that interstellar dust grains get aligned with respect to magnetic field. It did not take long time to realize that grains tend to be aligned with their long axes perpendicular to magnetic field. However, progress in theoretical understanding of the alignment has been surprisingly slow in spite of the fact that great minds like L. Spitzer and E. Purcell worked on the problem (see [23, 18, 19, 20, 22]). Formulating the adequate grain alignment theory happened to be very tough and a lot of relevant physics had to be uncovered.

Originally it was widely believed that interstellar grains can be well aligned by a paramagnetic mechanism [3]. This mechanism based on the direct interaction of rotating grains with the interstellar magnetic field required to have magnetic fields that are stronger than those uncovered by other techniques.<sup>1</sup> Later, a pioneering work by [20] showed a way how to make grain alignment more efficient. [20] noticed that grains rotating at high rates are not so susceptible to the randomization induced by gaseous collisions and introduced several processes that are bound to make grains very fast rotators. For decades this became a standard explanation for grain alignment puzzle, although it could not explain several observational facts, e.g. why observations indicate that small grains are less aligned than the large ones.

## 2 Relevant Physics

New physics of grain internal motion uncovered fairly recently explains inefficiency of alignment of small grains by Purcell's mechanism. [14] found that small grains flip frequently due to the coupling of rotational and vibrational degrees of freedom of a grain. As the result regular torques, e.g. torques due to ejection of H<sub>2</sub> molecules, get averaged out and grains rotate at thermal velocities. The paramagnetic alignment of thermally rotating grains as we mentioned earlier is inefficient (see [21]). Interestingly enough, [15] found that coupling of rotational and vibrational degrees of freedom happens most efficiently through the so-called nuclear relaxation that arises from nuclear spins of species within the grains. This relaxation makes grains of size  $\geq 10^{-5}$  cm rotate thermally, which makes the Purcell mechanism inefficient for most of dust in diffuse interstellar medium.

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<sup>1</sup>As discussed for instance in [13] the very small grains are likely to be aligned by this mechanism and this can explain the peculiarities of the UV part of the spectrum of the polarized radiation observed (see [12]). The efficiency of the Davis-Greenstein mechanism increases as the grain size decreases.

### 3 Radiative Torques

Introduced first in [4] and [5] the RT were mostly forgotten till a more recent study [6], where their efficiency was demonstrated using numerical simulations (see also [7, 24], [2]).

The RT make use of interaction of radiation with a grain to spin the grain up. Unpolarized light can be presented as a superposition of photons with left and right circular polarization. In general, the cross-sections of interaction of such photons with an irregular grain will be different. As the result of preferential extinction of photons with a particular polarization the grain experiences regular torques and gets spun up.

The predictions of RT mechanism are roughly consistent with the molecular cloud extinction and emission polarimetry [16] and the polarization spectrum measured [11]. RT have been demonstrated to be efficient in a laboratory setup [1]. Evidence in favor of RT alignment was found for the data obtained at the interface of the dense and diffuse gas ([13] and Figure 1).

While it was originally believed that RT cannot align grains at optical depths larger than  $A_v \approx 2$ , a recent work [2] demonstrated that the efficiency of RT increases sharply with the grain size and therefore bigger grains that exist within molecular clouds can be aligned for  $A_v$  more<sup>2</sup> than 10. Large grains may constitute an appreciable part of the total mass of dust within a cloud, while still be marginal in terms of light extinction. Therefore a non-detectable polarization in optical and near infrared does not preclude substantial polarization to be present in submillimeter. This makes submillimeter polarimetry the preferred tool for studies magnetic fields and magnetic turbulence in molecular clouds.

### 4 Relation to Magnetic Field

Most of the processes produce grain alignment in respect to magnetic field, even if the alignment mechanism is of non-magnetic nature. This is true due to the rapid precession of grains about magnetic field. This precession stems from the substantial magnetic moment that grains get due to their rotation [5]. Indeed, a rotating paramagnetic body gets a magnetic moment due to a Barnett effect. The corresponding period of grain precession  $\tau_L$  is  $\sim 10^5 B_3^{-1} a_{-5}^2$  s, where the external magnetic field is normalized over its typical interstellar value of  $3 \times 10^{-6}$  G and grain size is chosen to be  $a = 10^{-5}$  cm. This means that for turbulent motions on time scales longer than  $\tau_L$  grains orientation in respect to magnetic field lines does not change as the consequence of the adiabatic invariant conservation.

If the alignment happens on the time scales shorter than  $\tau_L$  the dust orientation may not reflect the magnetic field. For the RT such a fast alignment will happen with longer grain axes perpendicular *to the direction of radiation*, while the fast mechanical alignment will happen with longer axes parallel to the flow<sup>3</sup>. The mechanical and RT alignment takes place on the time scale of approximately<sup>4</sup> gaseous damping time, which is for interstellar medium is  $\sim 10^{11} T_{100}^{-1/2} n_{-20}^{-1} a_{-5}$  s, where typical temperatures and densities of cold interstellar medium, which are respectively 100K and  $20 \text{ cm}^{-3}$  were used for the normalization. Note, that magnetic alignment takes place over even longer time scales, namely,  $\sim 10^{13} B_3 a_{-5}^2$ . Therefore in most cases the magnetic field indeed should act as the alignment axis.

It is worth noting that the turbulent fluctuations over time scales that are shorter than  $\tau_L$  *do not* suppress alignment. The rapidly precessing grains preserve their orientation to the local direction of magnetic field and undergo the alignment even when this local direction is changing its orientation in space. In this respect grain alignment is a local process that can reflect local direction of magnetic field for magnetic ripples larger

<sup>2</sup>The studies by one of us reveal that for fractal molecular clouds the alignment can be present for cores with  $A_v$  of 30. In addition, as large grains do not flip frequently the Purcell torques and Purcell's alignment gets efficient as well.

<sup>3</sup>The rule of thumb for mechanical alignment is that it tends to minimize the grain cross section for the grain-flow interaction, while for RT is that the grain precession is minimized.

<sup>4</sup>The mechanical alignment happens faster due to the fact that the flows are supersonic. This is an important difference to be considered for transient alignment, but has marginal consequences for the most of interstellar gas.

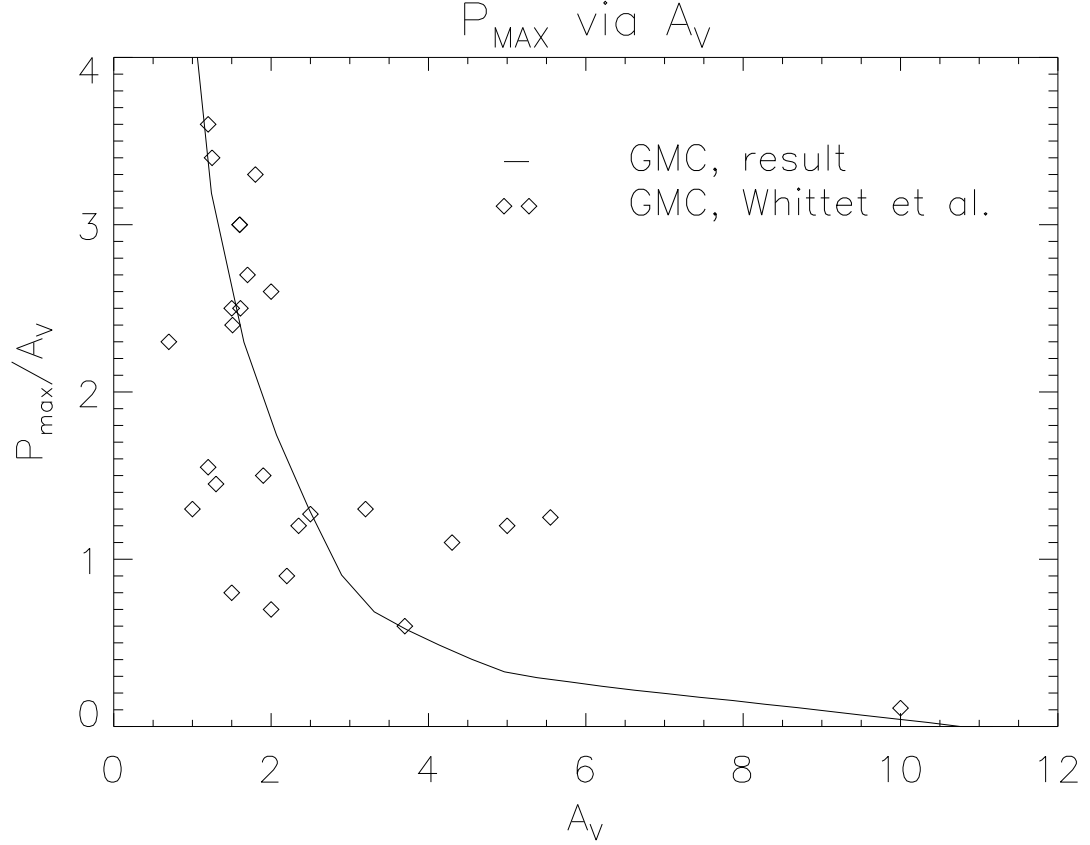


Figure 1:  $p_{\max}/A_V$  as function of  $A_V$  from our calculations with radiative torques and the observation data by Whittet et al. (2001). Observational error bars are not shown. The flattening of the observational results at  $A_V > 4$  is likely to be the consequence of the cloud being inhomogeneous. We use a homogeneous slab and the MRN distribution of dust with  $a_{\max} = 0.35\mu\text{m}$ . Work done with Mr. Hoang Thiem.

than  $\tau_L V_A$ , where  $V_A$  is Alfvén speed. Whatever is the process of alignment, if it aligns grains over timescale larger than  $\tau_L$  the alignment is perpendicular or parallel to magnetic field. This allows to study some aspects of magnetic turbulence without asking fundamental questions about mechanisms of alignment.

## 5 Summary

Grain alignment is a subject that is very rich in terms of physical processes. The advances in understanding of grain alignment processes made the theory predictive and allowed to explain the observational data available. This enables one to reliably interpret observed polarization in terms of the underlying magnetic fields.

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